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SYNOPTIC USE OF RADIATION MEASUREMENTS FROM SATELLITE TIROS II [1]

SIGMUND FRITZ AND JAY S. WINSTON

Meteorological Satellite Laboratory, U.S. Weather Bureau, Washington, D.C.

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ABSTRACT

TIROS II measurements of infrared radiation in the 10-micron "water-vapor window" on one orbital pass over the United States are examined in detail relative to the field of cloudiness as derived from TIROS II television pictures and from other meteorological data. The radiation data are found to portray clearly the large-scale systems of middle and dense high cloud overcast, a capability that exists both day and night. Through use of information about the vertical and horizontal temperature fields, useful quantitative estimates of the heights of the tops of cloud systems are derived. In cases where there is a low overcast, the window measurements in themselves may not distinguish clouds from clear areas; but during daytime if television pictures are available, the window measurements can clearly show where a cloud overcast is low in height. Some tentative conclusions about the partial transparency of cirrus clouds to infrared radiation are also presented.

1. INTRODUCTION

TIROS I produced thousands of excellent photographs of cloudiness on many scales (e.g., [1, 2, 3]). However, it was rarely possible to ascertain from the pictures alone the levels in the atmosphere at which the clouds were located. Moreover, the TIROS cameras depend on reflected solar energy, and thus can operate only in daylight.

To assist in overcoming these limitations, as well as for other purposes, TIROS II,[2] which was launched on November 23, 1960, carried several radiometers in addition to two television cameras [4, 5, 6]. One of these radiometers measured the energy emitted by the Earth in the so-called "water-vapor window", the wavelength interval from about 8 to 12 microns. Since water vapor has a relatively small effect on the "window" measurements, the satellite measures the energy emitted by the "surface" which it "sees" in the spectral range of the instrument. An overcast (undercast as "seen" by the satellite) of dense middle and high clouds, whose tops are cold, emits relatively little energy. By contrast, nearby areas of lower clouds or broken clouds, or cloudless areas generally emit more energy. If the radiating surface is opaque, the energy emitted by this surface and measured by the satellite is related to the temperature of this surface; otherwise the radiation is a complicated function of the cloud amount and cloud structure.

The water-vapor window on TIROS II was rather broad. Although the entire radiometer was not calibrated in detail for spectral response, the combination of the spectral effects of the filter and of the chopper [3] [4] are shown in figure 1. It is assumed that all other surfaces within the instrument had uniform spectral characteristics. The filter transmitted mainly the radiation between about 7.5 and 13 microns. There also was a

[1] This research has been partially supported by the National Aeronautics and Space Administration.

[2] The altitude of TIROS II was about 450 miles, and the subsatellite point moved between 48° N. and 48° S.

[3] The chopper is a rotating disk, half mirrored and half black, which alternately reflects energy from the Earth and from space to a sensing element. This is the basis for producing an alternating signal from the satellite.

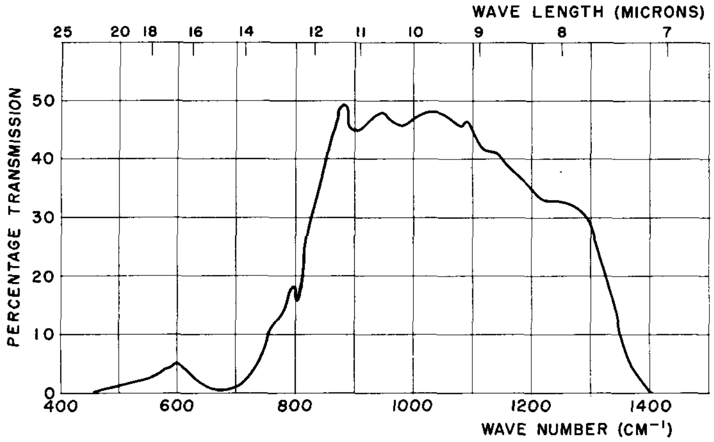

FIGURE 1.—The spectral transmission of the TIROS II "window" radiometer.

small transmission in the region near 17 microns, but calculations of the energy emitted from the Earth at this wavelength indicate that this contributed very little energy to the total energy received at the satellite from the Earth.

The radiometers were calibrated before launch at Cape Canaveral. Some uncertainty exists as to the exact value of the radiation measured [7], especially when the radiometer was viewing a cold source on the Earth. Nevertheless, there are indications that the pattern of radiation is basically correct, since even for low (cold) radiation values there is an error of no more than a few degrees.

The application of these satellite radiation data to estimate cloud amounts and heights will be most useful in oceanic areas and other sparse-data areas. But the case study described in this paper was made over the United States so that the results could be checked with good conventional data.

During orbital pass 4, on the day of launch, good satellite measurements were made over the United States between about 1805 and 1815 GMT. A few radiative results from the first four passes have already been described [4]. In this paper the window data obtained on pass 4 over the United States are discussed in greater detail together with associated picture nephanalyses and conventional meteorological data.

With use of the best calibration available, values of radiation intensity were expressed in terms of "effective" or "equivalent" temperature, T_E, defined as follows:

Let I_λ be the intensity of the energy at the wavelength λ, coming from the Earth to the satellite; also let ϕ_λ be the spectral response of the radiometer as shown in figure 1. Then we may define an effective black body temperature, T_E, from

$$\int_0^\infty \phi_\lambda B_\lambda(T_E)d\lambda = \int_0^\infty \phi_\lambda I_\lambda d\lambda. \qquad (1)$$

Here $B_\lambda(T_E)$ is the Planck black-body intensity for a temperature T_E. The right side of equation (1) is the actual intensity which passes through the instrument from the Earth and produces the final signal response. The left side is the intensity which would be sent to the sensing element in the satellite from a black body at the "equivalent" temperature T_E. Thus from the satellite signals, which are produced by I_λ, it is possible to determine the value of T_E graphically [7]. The satellite measurements in terms of T_E are shown in figure 2. There was an uncertainty of about 40 seconds in the time at which the data were observed by the satellite. To make the overall pattern agree with the known position of the synoptic cloud pattern, the *whole* radiation map was moved east-southeastward about 140 n. mi. The *pattern* of the map was not modified at all.[4]

The dot-dashed lines in figure 2 refer to conditions when the zenith distance of the satellite from the observed point on the Earth's surface was 60° or more. Under these conditions, the satellite radiometer "looks" through a long path of water vapor which generally tends to reduce the value of T_E. Preliminary studies for the data considered in this paper indicated that when the zenith distance was less than 60°, the influence of the increased water vapor path was small.

2. SATELLITE RADIATION AND PICTURE DATA IN RELATION TO CLOUD COVER

Figure 2 shows a broad, northeast-southwest band of low temperatures (cold radiative sources) in the eastern part of the United States with lowest temperature about 240° K. From the earlier discussion regarding the low emission from cold sources, this cold band obviously represented an area of dense clouds extending to high levels. As indicated in figure 2 these low temperatures generally straddled the surface frontal zone through this region. The central United States was occupied by a broad region of fairly uniform, high temperatures ranging from about 280° to 285° K.; this area must have been either (1) cloudless, (2) covered by warm, low clouds, or (3) covered by scattered or broken clouds over a warm surface. Finally, farther west, a complicated isotherm pattern existed with the lowest temperatures, less than 250° K. over South Dakota, corresponding to a region of cold clouds, with substantially warmer areas more than 270° K., over nearby States.

The cloud distribution deduced from figure 2 can be compared with a nephanalysis made from the cloud pictures televised by TIROS II, during orbital pass 4 (fig. 3). This figure shows a widespread region of cloud overcast in the eastern and southern United States with a sharp boundary separating the overcast region from a clear area over much of the central United States. Thus,

[4] As this article was going to press a new estimate of the error in time was received from the NASA (verbal communication). The new estimate indicates that the original time (before our correction was applied) was in error by about 48 sec. This would have required that the radiation map be moved east-southeastward about 175 n.mi. This new estimate is probably not significantly different from the 140 n.mi. by which we moved the data in figure 2.

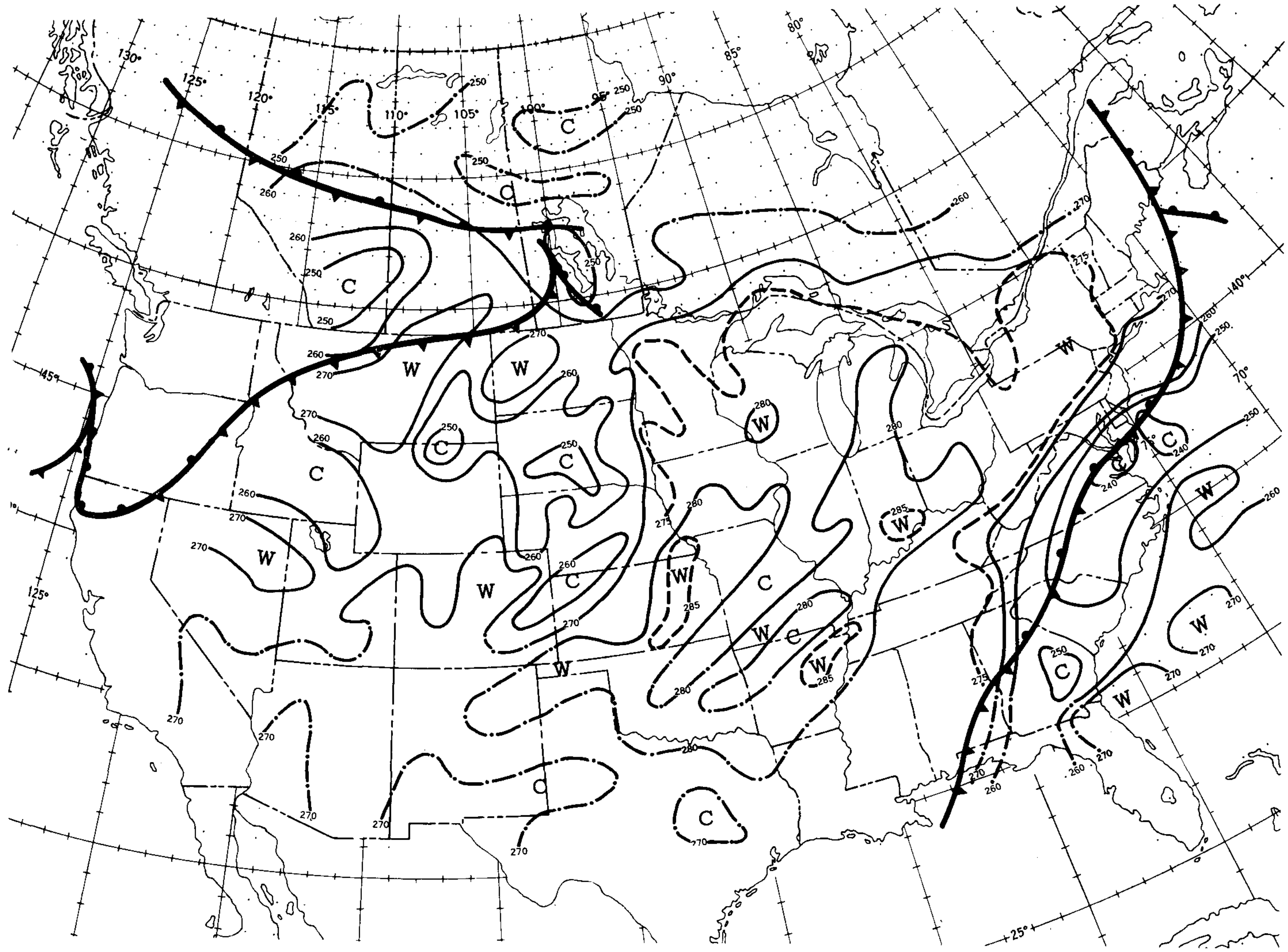

FIGURE 2.—Effective temperature, T_E, in °K., measured by TIROS II on orbital pass 4, 1805–1815 GMT, November 23, 1960. The path of the satellite on this pass was from the northwest corner of the country east-southeastward across southern Lake Michigan and across the east coast over Virginia. The dot-dashed isotherms on the northern and southern edges of the data are in regions where the zenith distance of the satellite from the observed point on the Earth's surface was 60° or more. The dashed lines are intermediate 5° K. isotherms which show more detail where there is wide spacing of the solid 10° K. isotherms. Centers labeled W and C indicate maxima and minima, respectively, of effective temperature. Surface fronts taken from the 1800 GMT sea level analysis of the National Meteorological Center (NMC) are indicated by conventional symbols (see fig. 4).

the high temperatures over the central United States in figure 2 were associated with an area mainly devoid of clouds. However, there was an overcast over the South Central States which must have consisted of warm, low clouds. The more complicated pattern of overcast, broken, and clear areas over the Plains and eastern Rockies (fig. 3) was related to the radiation data too, with lower temperatures generally in zones of broken to overcast skies and higher temperatures where thinner clouds or possibly clear skies existed. Thus on an overall basis, figures 2 and 3 agree well.

Inspection of the surface weather map (fig. 4) and the cloud cover analysis based on surface synoptic data, radiosonde data, radar reports, and pilot reports (fig. 5) in comparison with figures 2 and 3 shows that the satellite data gave an excellent overall picture of the synoptic cloud distribution over the area of coverage. The broad overcast in the East, where low effective temperatures were found, was associated with a quasi-stationary front on both sides of which substantial rainfall was occurring. It is interesting that the 250° K. isotherm in figure 2 generally encompassed most of the rain area shown in figure 4. In other words the rain coincided with the zone where the cloud tops were highest and figure 5 shows that the clouds at the top of this portion of the overcast area were cirrostratus. Further discussion of cloud heights will be given in the next section.

For the complex cloud pattern over the Plains and the Rockies, the two nephanalyses (figs. 3 and 5) were generally similar. It is not surprising, however, that the satellite nephanalysis did not indicate much of the eastern portion of the cirrus and cirrostratus (scattered,

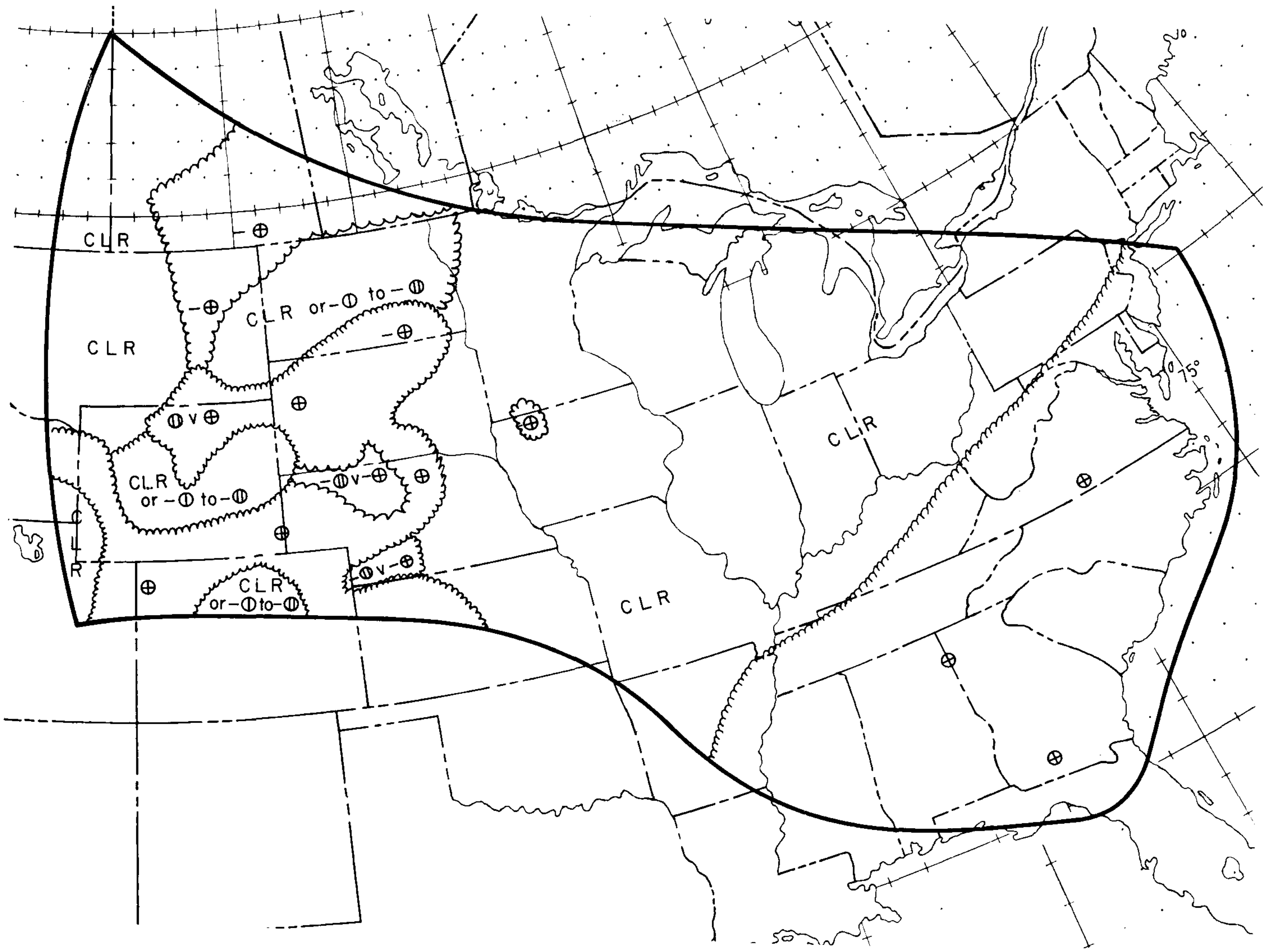

FIGURE 3.—Nephanalysis based on TIROS II cloud pictures taken on orbital pass 4, 1805–1815 GMT, November 23, 1960. The symbols ⊕, ⌽, and ⦶ refer respectively to overcast, broken, and scattered cloudiness, while CLR refers to apparently clear skies. The minus sign indicates thin cloudiness and V means variable. The solid line shows the approximate outer limit of view in the sequence of pictures.

broken, and overcast) over Minnesota, Iowa, eastern Nebraska, and the eastern Dakotas. This inability to see thin cirrus clouds in the satellite pictures was pointed out for TIROS I [8]. Since the quality of the wide-angle pictures was substantially poorer on TIROS II, it was to be expected that this thin cirrus cloudiness would not show up well.

Likewise scattered cloudiness over the Lower Lakes and Pennsylvania (fig. 5) did not show up in the TIROS nephanalysis (fig. 3). These clouds were reported to be stratocumulus with some higher cirrus over the Lower Lakes. Again because of the poor quality of the TIROS II pictures such scattered cloudiness could not be detected. Even with the TIROS I wide-angle camera [8] the identification of scattered, small cumulus cloud fields was uncertain.

Aside from these scattered clouds a broad area from the Great Lakes southwestward to Oklahoma and western Texas was clear (fig. 5), in agreement with the TIROS nephanalysis (fig. 3) and the high effective temperatures (fig. 2). A comparison of effective temperatures with the surface air temperatures in this region showed rather close agreement (i.e., within about 2°–3° C.). This agreement is probably somewhat better than one would expect to find on the average, since the radiation in the window region is largely dependent upon the temperature of the Earth's surface rather than the air temperature. Moreover, the absorption and emission by the overlying atmosphere usually makes the effective radiation temperature, T_E, lower than that of the surface itself. To see to what extent the atmosphere influences T_E, calculations of the energy leaving the Earth were made with several ground surface temperatures and with the overlying atmosphere given by the radiosondes at the appropriate times; the effect of ozone was also estimated. The results indicate that for the mid-United States, near noon on November

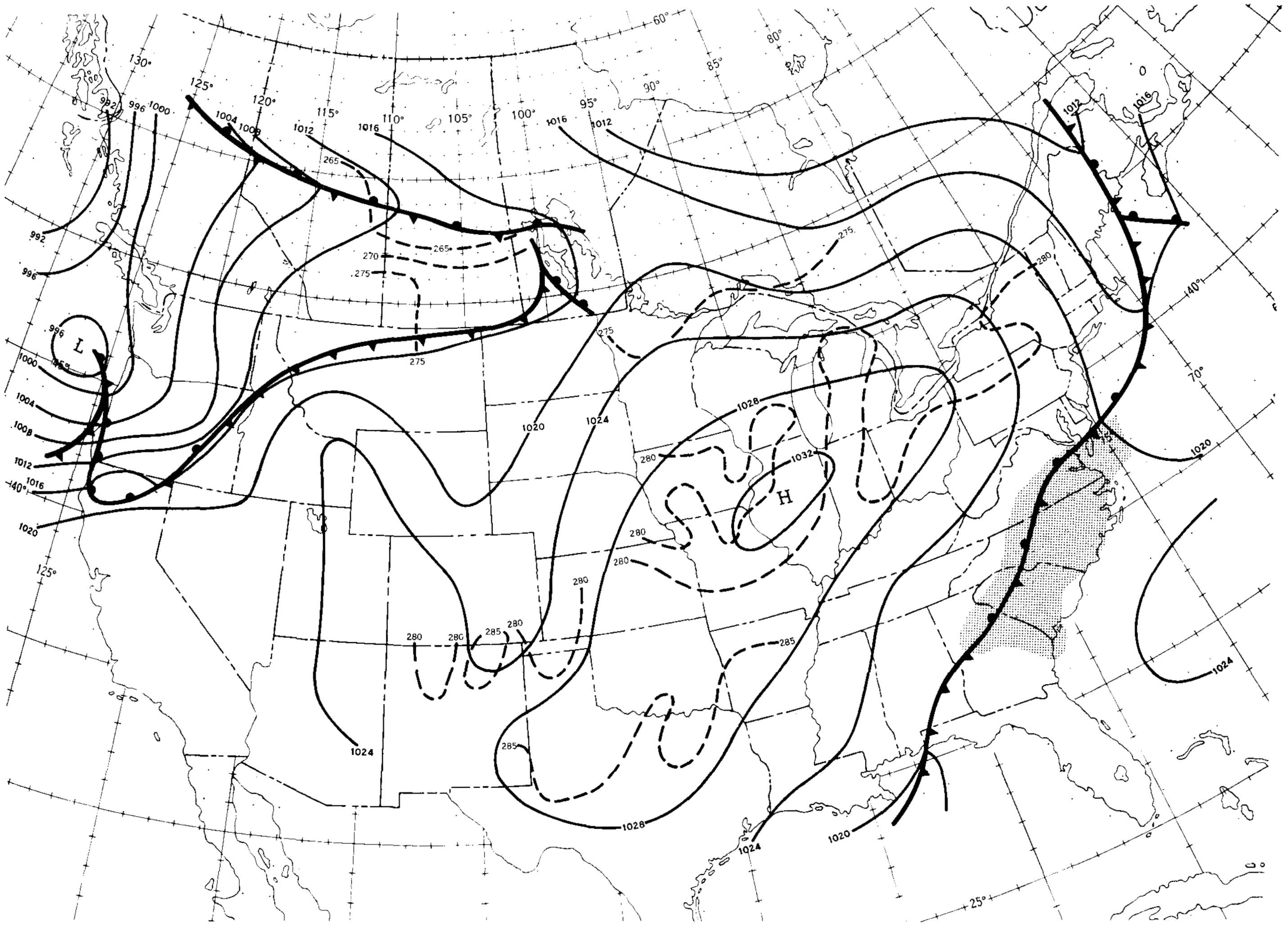

FIGURE 4.—Surface weather map for 1800 GMT, November 23, 1960. Isobars (solid lines) and fronts are taken from the NMC analysis. Area of precipitation along the east coast frontal zone is shaded. Dashed lines are isotherms of surface air temperature drawn only in clear or scattered cloud areas at intervals of 5° K.

23, the overlying atmosphere had the effect of reducing T_E by about 3°–5° C. below the surface temperature. The temperature of the actual surface was, of course, not precisely known, but various studies [9] suggest that near noon at this latitude and at this time of year, the surface temperature in vegetated areas is about 1°–3° C. warmer than the air at 3 feet above the ground, where the temperature is roughly comparable with the temperature in the conventional shelter. Thus considering the ground to be about 2°–3° C. warmer than the air shelter temperature, and considering that T_E should be about 3°–5° C. less than the surface temperature, it is not surprising that T_E was close to the air temperature in the shelter for cloudless conditions in this case.

3. ESTIMATION OF HEIGHTS OF CLOUD TOPS FROM RADIATION DATA

The effective temperatures in the regions of overcast cloudiness are essentially related to the temperatures, and hence to the elevations, of the cloud "tops." For maximum synoptic utility of a nephanalysis based on satellite cloud pictures, it would be most valuable to use the effective temperatures to make a quantitative estimate of the heights of the cloud tops. To do this it is necessary to know the three-dimensional temperature distribution in the atmosphere. For some places over the globe this temperature distribution is known quite well, whereas in many areas of the world (oceans, sparsely populated areas) it is known only approximately at best. However, for the Northern Hemisphere north of approximately 15° N., the National Meteorological Center now routinely produces (by objective methods) isotherm patterns for the 850-, 700-, 500-, and 300-mb. pressure surfaces. Also isotherms can readily be drawn on the surface map from the fairly numerous surface synoptic reports. Thus at any point north of latitude 15° N., an approximate "sounding" can be constructed based on the analyzed isotherms for these various constant pressure charts and for the surface map. These temperature-height curves can then be used to

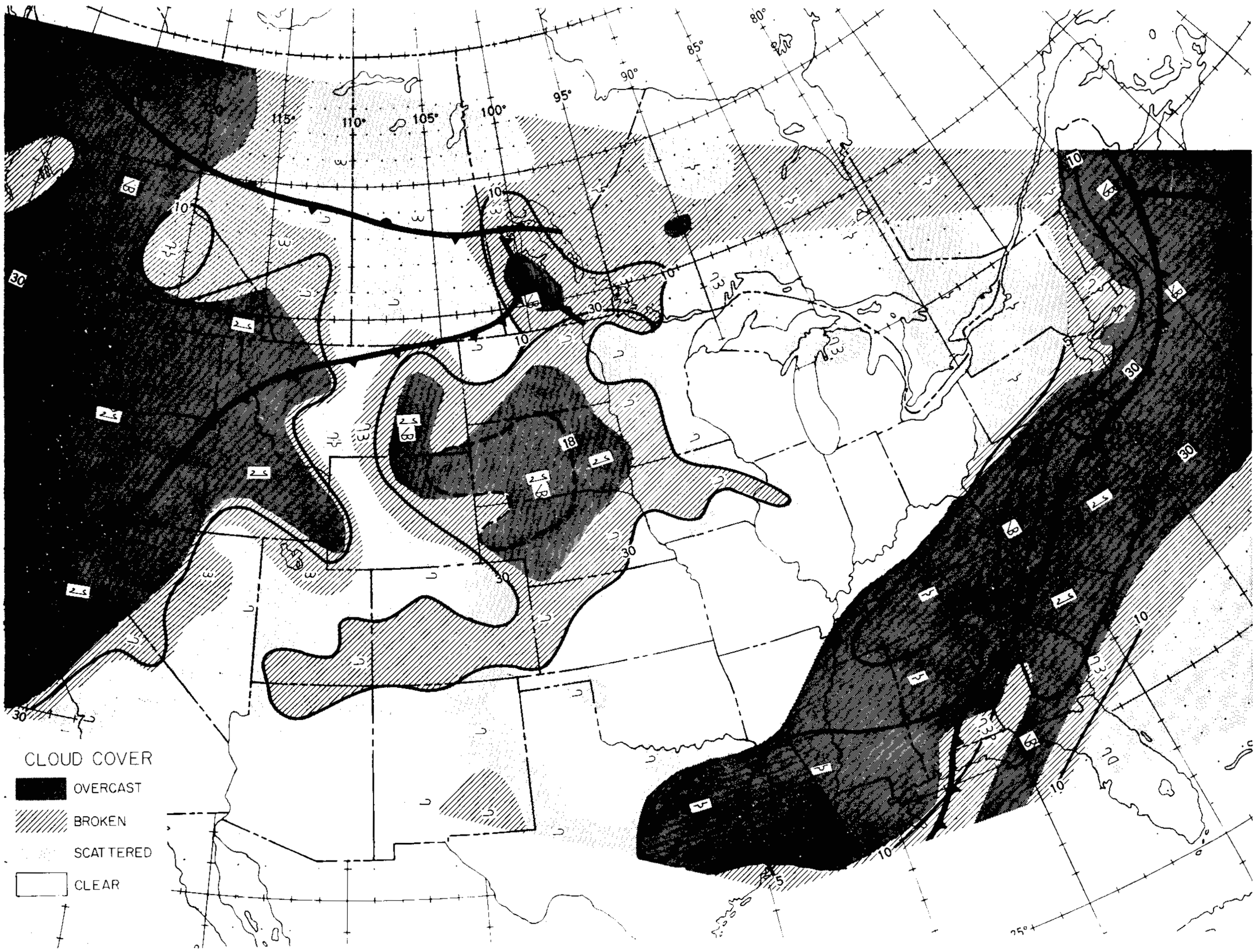

FIGURE 5.—Cloud cover chart for 1800 GMT, November 23, 1960 based on conventional meteorological data (i.e., surface observations, radiosonde reports, pilot reports, and cloud radar). Various lower, middle, and upper cloud types are indicated except in overcast areas where the type of only the upper cloud layer is generally shown. Solid lines are contours of the heights (labeled in thousands of feet) of the tops of the highest cloud layers in overcast and broken areas. The broken contour over South Dakota, Nebraska, and Wyoming outlines the region of a middle-cloud overcast with tops near 18,000 ft. The fronts are the same as shown in figures 2 and 4.

assign a height to each effective temperature at any location over the Northern Hemisphere. Admittedly such height estimates would be only approximate in some places (perhaps errors of a few thousand feet would not be uncommon), but such a hemispheric cloud top chart for overcast areas would nevertheless be very desirable. In regions of broken clouds the values of T_E and corresponding cloud top height will be more difficult to interpret; the interpretation of the satellite data for broken cloud areas has not been attempted here.

This height-determination procedure was applied to the data in figure 2 to obtain the height field shown in figure 6. In arriving at this height field no account was taken of cloud amount; heights were assigned to every effective temperature and the "soundings" were simplified through use of only constant pressure and surface maps. Temperatures on constant pressure surfaces for 1200 GMT, and surface temperatures for 1800 GMT, November 23, 1960, were used to estimate "soundings" closest to the time of the satellite data (about 1810 GMT).

Figure 6, together with figure 3, suggests that the cloud tops in the overcast area over the eastern United States varied in height from less than 5,000 ft. to over 27,000 ft. In general this height distribution agrees with the estimate of cloud types and ceiling heights obtained from the available conventional data as shown in figure 5. The cirrostratus clouds over Virginia and the Carolinas were generally somewhat higher than the estimate in figure 6; pilot reports over this area and the cloud radar at Washington, D.C. (fig. 7) showed that the tops of the cirrostratus were at about 32,000 ft., with bases near 25,000 ft. The radar record also indicated that the

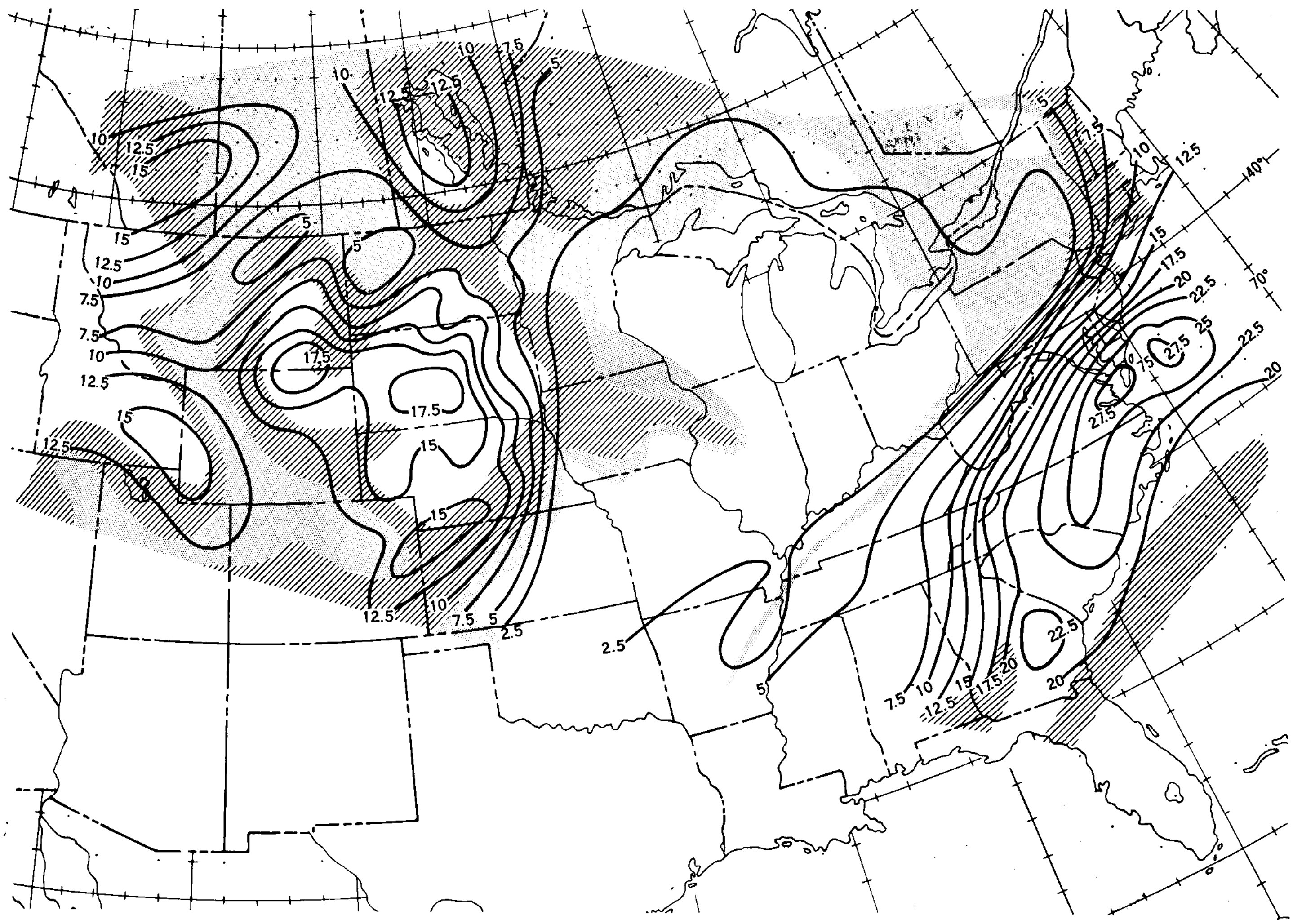

FIGURE 6.—Heights of cloud tops in thousands of feet for 1800 GMT, November 23, 1960 as estimated from TIROS II measurements of effective temperature, T_E, and from vertical soundings based on analyzed temperature fields on standard constant pressure charts. Areas of broken (hatched) and scattered (dotted) cloudiness (as shown in fig. 5) are indicated in view of the ambiguity in such cases of height estimates based on effective temperatures measured by TIROS II.

cirrostratus had a sharp boundary on its west side. This boundary passed over Washington shortly after 1830 GMT, about 15–20 minutes after the time of the TIROS II observation. Below the cirrostratus was a layer of altostratus clouds with tops near 14,000 ft. As figures 2 and 6 indicate, there was a very strong gradient in the radiation data in the area of Delaware, Maryland, and northern Virginia. This undoubtedly corresponded to the cloud boundary where the satellite radiometer swept across the edge of the high cloud and then on to the altostratus cloud to the north and west. This would have been true, of course, only if the uppermost cloud contributed appreciably to the radiation. The more gradual decrease in height (and increase in T_E) across Pennsylvania and West Virginia was probably associated with a change from an overcast of middle clouds to broken clouds and then gradually to clear skies. In this discussion of the reality of the radiation gradients, it should be pointed out that the resolution of the radiometer is about 40 miles when the instrument points straight down. That is, in drawing the data for figure 2, measurements near the east-west center line of the diagram were available for about every 40 miles. Although noise present in the system sometimes reduces the resolution, each measurement represents an average over about 40 miles.

The portion of the overcast over Tennessee, Alabama, and Mississippi (figs. 3 and 5) was indicated as having tops between about 3,000 and 7,500 ft. (fig. 6). This corresponds within a few thousand feet with estimates made from radiosonde data and pilot reports (fig. 5). Thus the radiation data readily distinguished the lower cloud tops over the South from the much higher cloudiness over the East and Southeast. On the other hand, if cloud photographs had not been available (e.g., at night) and if conventional data were also lacking (e.g., over a data-sparse area), it would have been difficult to distinguish this lower cloud region from the nearby cloudless

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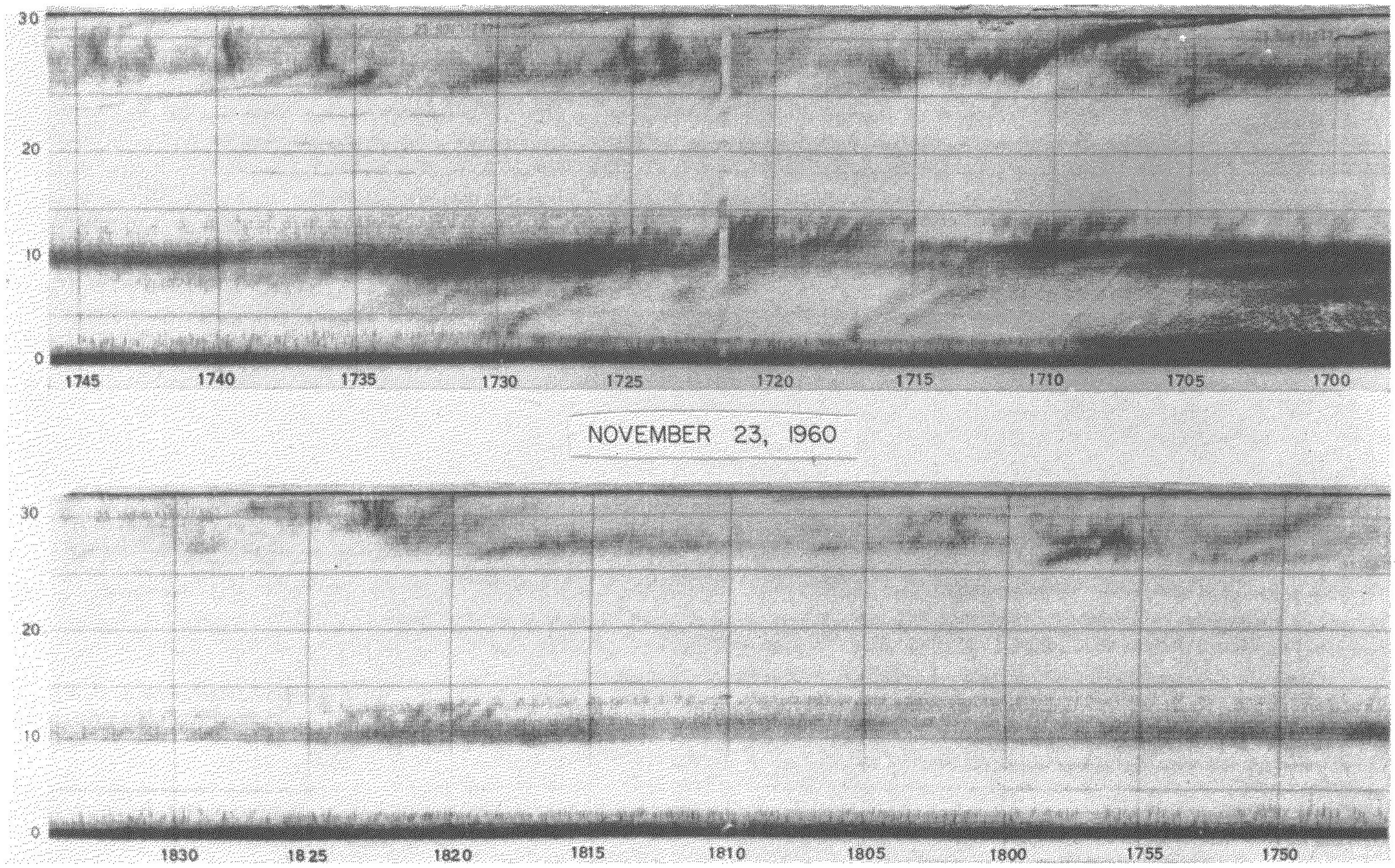

FIGURE 7.—Trace of the cloud base and top radar at Washington, D.C., between about 1700 and 1830 GMT, November 23, 1960. Height scale is labeled in thousands of feet. Middle and upper cloud layers appear dark in this trace; lower clouds are not always detectable with this radar.

area to the northwest since the effective temperatures were very similar over both areas (fig. 2). However, this area could easily have been distinguished from the area of high (cold) clouds farther east even at night. Thus these radiation data can serve satisfactorily to detect large-scale middle and high cloudiness at night, but their fullest utility would be in the daytime when they would complement the cloud pictures.

The overcast area over South Dakota and eastern portions of Wyoming was cold ($T_E \sim 250°$ K.), corresponding to a cloud top height of over 18,000 ft. (fig. 6). According to the surface reports in that area an altostratus overcast existed there, and from the sounding at Rapid City the top of this overcast was estimated to be at about 18,000 ft. The outline of this altostratus overcast is indicated by the dashed 18,000-ft. line in figure 5. From all indications it was overlain by a *thin* broken to continuous layer of cirrostratus, which did not seem to have much effect on the radiation.

Surrounding these western higher (cold) areas in figure 6 were lower (warm) areas with heights as low as 5,000 ft. These were associated with the clear to scattered cloudiness areas over North Dakota and Montana (figs. 3 and 5). Over western Wyoming (and extending into Montana) a minimum height axis of less than 12,500 ft. paralleled an area interpreted as clear in the pictures (fig. 3). This axis lies along the Continental Divide and the radiation values may have been related to the temperatures of many of the mountain peaks which are more than 10,000 ft. high.

4. SOME REMARKS ABOUT INFRARED EMISSION FROM CIRRUS CLOUDS

In regard to the results in relation to clouds, it is of course well known that some clouds such as altostratus, stratocumulus, and nimbostratus are usually fairly opaque; that is, the energy which originates deep in the cloud does not emerge through the cloud top. Therefore, the energy which comes to space from such a cloud arrives from a shallow layer near the cloud top, and approximates the emission from a dense medium of uniform temperature. Cirriform clouds, however, are more diffuse and in such a diffuse medium particles throughout the depth of the cloud may contribute to the radiant energy emerging from the cloud top. If the cirrus cloud is not very thick it is not capable of interfering appreciably with the energy arriving from below. On the other hand, if the cirrus cloud is thick, a substantial contribution from the cirrus particles is to be expected.

An example of thin cirriform cloud, which was discussed earlier, was found over South Dakota where T_E corresponded closely to the temperature at the top of the altostratus at 18,000 ft. and seemed to be unaffected by the overlying cirrus. The thicker type of cirrostratus was found in portions of the frontal zone over the eastern United States (figs. 5 and 7). The lowest value of T_E observed by the satellite in this region was about 240° K. (fig. 2). The radiosonde temperatures at the top and base of this cirrostratus were 225° K. and 240° K., respectively; the top of the underlying altostratus had a temperature of 260° K. Considering these various temperature values, it appears that in this area energy reached the satellite from both the cirrostratus and altostratus clouds and that the energy contribution from the cirrostratus particles varied according to their depth or temperature.

This behavior of cirriform cloud in regard to infrared radiation is similar to the classical problem of emission from a star in which temperature varies in the vertical, a problem treated by Schuster [10]. Further study of satellite infrared measurements may give some additional insight into such optical properties of clouds for infrared radiation.

5. CONCLUSION

The satellite observations have shown that the radiation data in the 10-micron water-vapor window can detect the presence of large-scale overcast made up of middle or dense high clouds, at least in middle and low latitudes, and that this can be done both day and night. At the same time, radiation data also furnish an estimate of the heights of the tops of overcasts within a few thousand feet, although cirrus clouds, because they are partially transparent, are not clearly defined. When cloud pictures are also available during daytime, the radiation data can aid in the determination of the heights of the tops of low cloud systems.

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